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Review of the LHC Ion Programme

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Abstract

Since 1995, a non-negligible amount of boundary conditions have changed for the potential operation of the LHC as an ion collider. The aim of this paper is to review these modifications and evaluate their implications for the future performance of the machine. The revised set of parameters presented in this report should be considered as the official revised programme for the operation of the LHC machine with ions.

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1 Introduction

From a pure machine point of view, the LHC programme for ions has essentially not been modified since 1995 [1]. However, in the beginning of this year, it was recognised that some of the basic input parameters (e.g. cross-sections for nuclear effects, number of potential experiments) had to be modified, so that a complete review of the programme has become necessary. Consequently, it was decided to review the complete ion programme for the LHC. In a first step, the modified parameters are described and new limitations are introduced. Then, the implications of these modifications on the potential performance of the machine will be discussed. However, since the officially approved LHC ion programme refers to an operation with Lead (Pb) ions, implications for this type of ions will be considered first. The extension to lighter ions (referred to as Phase II) will be treated separately in the second part of the report. Finally some more specific scenarios like hybrid collisions addressed by the physicists (upgrade programme) are presented and their implications for the machine are discussed.

For completeness, it should be underlined that the whole programme presented in this note, although referring mainly to the LHC machine itself, has been checked with the relevant people for its compatibility with the whole chain of injectors (from the source to the LHC machine).

2 Scope of the review

The modifications and new aspects retained for the present approach can be summarised as follows:

- On the basis of new published results, the cross-sections for nuclear effects have been updated.
- The possibility and the implications with several experiments operating simultaneously with ions have been included.
- The minimum requirements on luminosity lifetime introduced in 1995 have been fundamentally revised.
- A new limitation related to ion losses has been introduced.
- A detailed proposal of the ions species available for the future operation has been established.
- New scenarios for some particular modes of operation have been considered.

As can be seen from the above, the updated LHC ion programme will sensibly differ from its previous version, with some non-negligible implications in terms of performance of the machine. The individual aspects of each topic are treated separately in the following sections.

3 Nominal operation with Pb ions

In this first section, we shall focus on the nominal LHC ion programme, i.e. the LHC as a Pb-Pb collider. As will be shown, it is for this mode of operation that the new boundary conditions will have the most significant implications.

3.1 Cross-sections for nuclear effects: Pb ions

The nuclear effects considered in the present approach are those resulting in the loss of the ions from the colliding beams. Three main processes belong to this category:

- The hadronic nuclear interaction, e.g. ions participating directly to the collisions. This effect is characterised by its cross-section σ_H.

– The electromagnetic dissociation where an ion is excited by a γ-nucleon interaction and subsequently decays (Weizsacker-Williams process). The cross-section for this reaction is referred to as σ_{emd}.
– A two-photon process resulting in the creation of an electron-positron pair, followed by the subsequent capture of the electron by the ion (electron capture). The corresponding cross-section is σ_{ec}.

Since the very first study on heavy ions in the LHC, the values of these cross-sections have been the subject of many discussions. However, recent publications based either on extrapolation from experimental data [2] or on theoretical estimates [3, 4] showed a clear convergence towards values which are sensibly larger than those used previously. It is therefore legitimate to include these new values in the present model. The new cross-sections for Pb ions used throughout this report are presented in Table 1.

Cross-section	Pb ions	[barn]
Hadronic	σ_H	8
E.m. dissoc.	σ_{emd}	225
e^--capture	σ_{ec}	204

Table 1: Cross-sections for nuclear effects: Pb ions in LHC.

Since we are primarily interested by the global ion losses resulting from these nuclear effects, we usually combine the latter in a single cross-section σ_{tot} which will account for the total losses. For Pb ions, the new total cross-section amounts therefore to $\sigma_{tot} = 437$ barns, which has to be compared to the value of about 280 barns used in the previous studies [1].

Remembering that the losses scale directly with the product of the total cross-section and the luminosity, it becomes clear that the new values for the cross-sections will seriously affect the luminosity lifetime of the machine. Furthermore, it should be stressed that the quoted values represent the losses related to a single collision point in the machine (1 experiment). In case LHC would be operated with 2 (or 3) experiments, the corresponding losses should be multiplied by a factor of 2 (or 3).

3.2 Number of Experiments and Luminosity Lifetime

As mentioned in the previous section, the new cross-sections for nuclear effects are expected to seriously affect the luminosity lifetime. Furthermore, if one considers more than one experiment participating in the ion programme, this immediately implies that the guidelines defined in Ref. [1] for the luminosity lifetime (i.e. luminosity half-life of 6.7 hours) have to be re-considered. This is illustrated in Figure 1, which represents the normalised luminosity as a function of the time the machine is in collision mode. The upper curve (CERN-95-05) serves as a reference and represents the situation described in Ref.[1] (one experiment and a luminosity half-life of 6.7 hours). The second curve (New-1exp) represents the same situation, except that the new values for the cross-sections have been introduced. As can be seen, the luminosity half-life reduces to 5 hours. For the third curve (New-2exp), the cross-sections are still the new ones, but a second experiment is included: the luminosity half-life drops to 3 hours. Finally, the fourth curve (New-3 exp) illustrates the case where three experiments are included, resulting in a luminosity half-life of 2.1 hours. Figure 1 is sufficiently explicit to emphasise that the new boundary conditions completely invalidate our previous assumptions concerning the luminosity lifetime. A new strategy is therefore required.

Another interesting observation follows from Figure 2, which illustrates the luminosity as a function of time for two experiments and different initial intensities (and therefore different luminosity half-lives). As can be seen, independent of the duration of the fill and, more important, independent of the luminosity half-life, the highest initial intensity yields the best integrated luminosity (and this, despite of the fact that the effects of both the nuclear effects and intra-beam scattering are included in the computations). As a consequence, it seems reasonable to abandon any constraint related to the luminosity half-life. However, constraints on the growth times related to intra-beam scattering (IBS) and more specifically on the growth time in the longitudinal plane cannot be relaxed. Indeed, one has to avoid that, due to the longitudinal blow-up, particles escape the RF bucket. As a consequence, a minimum longitudinal growth time of 10 hours will still be imposed for all the calculations presented in this report.

3.3 New limitation: quench limit

In case of electromagnetic dissociation and/or electron-capture, the ion is lost from the circulating beam. Recent computations [5] have shown that these ions are lost in the dispersion suppressors of the machine (although at different locations for the two processes). As shown in Ref. [4, 5], the total energy deposited by the lost ions is not a problem. However, the longitudinal density of power deposition turns out to be a serious problem for Pb ions and sets a severe limit on the maximum luminosity tolerable in order not to exceed the quench limit of the magnets (5 mW/cm^3). According to Ref. [5], for Pb ions, the quench limit is reached for a luminosity around:

$$5.0 \times 10^{26} cm^{-2} s^{-1} \quad < \quad \mathcal{L}_{max} \quad < \quad 1.0 \times 10^{27} cm^{-2} s^{-1}$$

The fact that the maximum acceptable luminosity can presently only be estimated within a factor of two relies on some remaining uncertainties related to the quench limit itself (5 mW/cm^3). For the present exercise, it has been decided to retain the upper limit:

$$\mathcal{L}_{max} \text{ (quench limit)} \quad = \quad 1.0 \times 10^{27} cm^{-2} s^{-1}$$

This new limitation therefore cancels the relative improvement obtained from the relaxation of the constraint on the luminosity half-life. Given this relatively low limit, alternative scenarios to optimise the integrated luminosity (e.g. squeeze of the beta function during the fill) will play an essential role in the particular case of Pb ions. However, since such a scenario is not foreseen for the initial operation of the machine, it will be discussed in a later section.

3.4 Revised parameters list for Pb ions

The luminosity being limited to $1.0 \times 10^{27} cm^{-2} s^{-1}$ (corresponding to 6.8×10^7 ions/bunch with 608 bunches), it is possible to establish a revised parameter list for the LHC as a Pb-ion collider. The corresponding list is presented in Table 2.

3.5 Nominal performance for Pb ions

With the initial machine parameters as defined in Table 2, it is possible to evaluate the behaviour of the luminosity as a function of time. Such a nominal performance is illustrated in Figure 3. For this evaluation, 2 experiments and a filling time of 3 hours have been assumed (the filling time is the effective time spent between two consecutive periods of data taking). The upper curve in Figure 3 represents the normalised luminosity as a function of the time of operation. One observes that the luminosity half-life under these

Energy per charge [TeV]	7
Centre-of-mass energy [TeV]	1148
Transv. norm. emitt. ϵ^* [μm]	1.5
β at the IP (coll.) β^* [m]	0.5
r.m.s. beam radius at IP σ^* [μm]	15
Crossing angle (per beam) [μrad]	$\leq$ 100
Longit. emittance ϵ_l [eVs/Q]	2.5
r.m.s. bunch length σ_s [cm]	7.5
r.m.s. energy spread σ_E/E (10^{-4})	1.137
Bunch spacing l_b [ns]	124.75
Number of bunches per ring k	608
Filling time per ring [min]	9.8
Number of ions per bunch N_b	6.8×10^7
IBS growth time (coll.) τ_ϵ [h]	15
Luminosity half-lifetime $\tau_{1/2}$ [h]	4.2
Initial luminosity [$cm^{-2}s^{-1}$]	1.0×10^{27}

Table 2: The LHC list of parameters: Pb ions, 125 ns bunch spacing and 2 experiments.

conditions is 4.2 hours, i.e. relatively short. Maybe more interesting is the lower curve which represents the average luminosity (integrated luminosity divided by the cumulated time for filling and physics). In case this curve is strongly peaked, the position of the maximum would indicate the optimum time of operation given the assumed filling time. As can be seen from the figure, the maximum is very flat for Pb ions, indicating that there is no pronounced optimum condition for the duration of the physics run.
However, a direct consequence of the relatively short luminosity half-life is that the time spent between the moment the beams are brought into collisions and the moment where the experiments start to take data (set-up time) will play an important role for the integrated luminosity. This is illustrated in Figure 4, which compares the average luminosity obtained when data taking starts immediately (upper curve) with the case where a set-up time of 20 minutes is required (lower curve). The importance of the set-up time is clearly visible and would be even enhanced with 3 experiments operating.

For the sake of completeness, Figure 5 illustrates the behaviour of the relative emittances of the beams (effect of IBS) during a nominal Pb run. As can be seen, both the longitudinal (upper curve) and the horizontal (lower curve) blow-ups of the emittances remain below 40 % over 10 hours, which indicates that IBS is not a dominant effect for Pb ions. This had to be expected since for Pb ions, the limitation is imposed by the quench limit and not by IBS.

4 From the nominal to the Phase II programme

So far we have concentrated on the officially approved LHC ion programme, i.e. the LHC as a Pb-Pb collider. We shall now move to the second part of the programme, which is referred to as the Phase II programme. The latter consists in collisions between lighter ions (A-A collisions). It should be emphasised that the Phase II does not include hybrid collisions (p-A collisions) which will be described in the upgrade programme later on.

4.1 LHC with lighter ions

In collaboration with the responsible people for the whole injector chain (including the source), a new list of possible ions has been established. It should be underlined that the list is the result of an optimisation process between the wishes expressed by the experiments and a review of the elements considered as advantageous for an ECR source. The resulting list of potential candidates is presented in Table 3.

Name	Symbol	A	Z
Tin	Sn	120	50
Krypton	Kr	84	36
Argon	Ar	40	18
Oxygen	O	16	8

Table 3: List of possible ions for future collisions in the LHC

As can be seen, this list shows a rather broad spectrum of possibilities. It should not be interpreted as a list of all the ions which will be collided in the LHC, but should rather help the experiments to make a choice of the elements which are best suited for their physics requirements.

4.2 Cross-sections for nuclear effects

In order to evaluate the potential performance of the LHC with these new types of ions, it is necessary to make an assumption on the cross-sections related to nuclear effects. The procedure followed here is to apply, for each type of ion, a scaling process, similar to what has been done for the Pb ions (the initial values are taken from Ref. [7]). It is likely that these scaled values will be refined in a near future, however, it is not expected that the effect of these corrections will sensibly influence the performance presented in this report. The retained cross-sections are listed in Table 4.

Ion	σ_H [b]	σ_{emd} [b]	σ_{ec} [b]	σ_{tot} [b]
Pb^{82}_{208}	8	225	204	437
Sn^{50}_{120}	5.5	44.5	18.5	68.5
Kr^{36}_{84}	4.5	15.5	3.0	23.0
Ar^{18}_{40}	3.1	1.7	0.04	4.84
O^{8}_{16}	1.5	0.13	$1.6\ 10^{-4}$	1.63

Table 4: Cross-sections for nuclear effects: ions in the LHC

4.3 Maximum bunch intensities and ultimate initial luminosities

In parallel to the evaluation of the cross-sections, it is also possible to evaluate the maximum bunch intensities and therefore the ultimate initial luminosities for which either one of the main limitations (quench limit or longitudinal IBS growth time of 10 hours) is reached first. The corresponding values are given in Table 5. It is interesting to observe that the newly introduced quench limit only affects Pb and Sn ions. Actually, for the latter, both limits (quench and IBS) coincide.

Ion	Limit	N_0^{max}	τ_{IBS} [h]	$\mathcal{L}_0$ [cm^{-2}s^{-1}]
Pb^{82}_{208}	Quench	6.8×10^{7}	15	1.0×10^{27}
Sn^{50}_{120}	Quench	2.8×10^{8}	10	1.7×10^{28}
Kr^{36}_{84}	IBS/Source	5.5×10^{8}	10	6.6×10^{28}
Ar^{18}_{40}	IBS/Source	2.2×10^{9}	10	1.0×10^{30}
O^{8}_{16}	IBS/Source	1.2×10^{10}	10	3.1×10^{31}

Table 5: Maximum bunch intensities and ultimate initial luminosities for ions in the LHC

4.4 Optimum operation scenarios for LHC with ions

Similarly to what has been done for Pb ions, the behaviour of the luminosity as a function of time can be simulated for each type of ions considered. The corresponding plots are qualitatively very similar to that illustrated for Pb in Figure 3 and are therefore not reproduced here. Instead the most relevant numerical results are summarised in Table 6. Here again, a filling time of 3 hours, 2 experiments and no set-up time have been assumed.

Ion	$\mathcal{L}_0$ [cm^{-2}s^{-1}]	$\mathcal{L}_{1/2}$ [h]	T_{opt} with T_f [h]	<L> with T_f [cm^{-2}s^{-1}]
Pb^{82}_{208}	1.0×10^{27}	4.2	5.7	4.2×10^{26}
Sn^{50}_{120}	1.7×10^{28}	5.2	6.5	7.6×10^{27}
Kr^{36}_{84}	6.6×10^{28}	7.0	7.5	3.2×10^{28}
Ar^{18}_{40}	1.0×10^{30}	7.4	7.8	5.2×10^{29}
O^{8}_{16}	3.1×10^{31}	5.0	6.3	1.4×10^{31}

Table 6: Initial luminosity ($\mathcal{L}_0$), luminosity half-life ($\mathcal{L}_{1/2}$), optimum duration of the fill (T_{opt}) and average luminosity (<L>) for an operation during T_{opt} for different ions in LHC. Assumed filling time T_f is 3 hours with 2 experiments operating.

5 From Phase II to the upgrade programme

The straightforward extension of the Phase II scheme is to consider hybrid collisions, i.e. collisions between different types of ions. For this particular kind of operation, one should clearly distinguish between the different options which could be envisaged. It is worth underlining that these modes of operation can only be considered as a future upgrade programme. For this reason, the expected performance in terms of luminosities will not be addressed in this report.

5.1 p - A collisions

Collisions between protons and ions are in principle possible, since two independent RF systems are available. However, such an operation also requires the availability of two independent timing systems. Although the necessary cabling is already included in the baseline layout, the acquisition of the dedicated electronics remains to be discussed. Apart from this relatively minor implementation, p-A collisions in the LHC should not be a problem.

5.2 d - A collisions

The question whether d-A collisions will be available in the LHC is still under investigation. The reason is that the same source has to be used for the production of both the protons and the deuterons. In other words, while the source would be operated to produce deuterons, there would be no protons available for the CERN machines. The final answer will therefore strongly depend on the time required for the source to switch back and forth between protons and deuterons production.

Apart from this potential problem, d-A collisions are not expected to present more difficulties than p-A collisions.

5.3 A - B collisions

Contrary to the two previous modes of operation, any collisions of the type A-B (collisions between two different type of ions) is presently excluded for the LHC. The reason for this decision is that the production of the second type of ions would require the availability of an additional source. Such an extension is presently not foreseen.

5.4 Possible modifications

It is worth underlining that the arguments presented in the two previous sections reflect our present understanding of the situation. It is however not excluded that the latter might be modified.

As a matter of fact, for d-A and A-B collisions, the PS division is presently studying a new layout for the Linac 3, with possibly two sources and a switchyard allowing to produce two different types of ions, including deuterons. Actually, alpha-particles could even be proposed as an alternative to deuterons for the present d-A collision programme. A final report will be presented by the beginning of 2001, after the corresponding issues will have been discussed in the relevant committees [6].

6 Particular machine configurations

Among the numerous requests discussed with the experiments, two specific configurations emerged as particularly interesting for their potential impact on the physics yield. Since these configurations represent real challenges, they cannot be included in the baseline LHC programme.

6.1 Reduction of the beam size during physics (β-squeeze)

As mentioned previously, in the case of Pb ions, the quench limit sets an upper limit to the achievable luminosity. Remembering that the luminosity is a function of both the bunch population and the beam sizes (though with different scaling laws), it is therefore possible to increase the bunch population and maintain the same luminosity, provided the beam size is "artificially" increased. The size of the beam at the interaction point can be controlled by acting on an optics property of the machine, namely the so-called β-function.

The proposed scheme is therefore the following: the LHC is filled with bunches containing the maximum possible number of ions per bunch (limit given by the source or by IBS considerations) and the initial beam size is adjusted such that the resulting luminosity coincides with that imposed by the quench limit. As the bunch population decreases with time during physics, the beam size is accordingly reduced (via a reduction of the β-function) such that the luminosity remains constant. The scheme can be applied in a stepwise manner until the β-function reaches its nominal value for physics, i.e. $\beta = 0.5$ m. Given the extremely short luminosity half-life of the nominal scheme (without squeeze), the possibility to maintain the luminosity constant during part of the physics run would obviously greatly improve the integrated luminosity. However, such a scheme is a real challenge for operation. Indeed, the magnets used for the β-squeeze are simultaneously used to provide both the correct crossing angle and adjust the collision conditions. Changing the β-function will thus cause the beams to separate and a re-adjustment of the collisions parameters will be necessary. Such a procedure is very delicate and could potentially be a source of background for the experiment.

The possible gain of this scheme is high enough that it is worth trying it. However, it will require a perfect understanding of the machine behaviour and could therefore only be considered once running the LHC has become routine operation.

6.2 Physics at intermediate energies

The possibility of colliding protons at intermediate energies (smaller than 7 TeV) in order to obtain useful comparisons with ions data has been repeatedly presented as an essential option. In principle, this option should be possible, provided collisions take place with a detuned optics (the value of the β-function will depend on the energy considered). This restriction is imposed because the beams are larger at lower energy. Trying to squeeze to β=0.5 m would be incompatible with larger beams mainly for two reasons: first the aperture in the triplet would be insufficient and secondly the machine would be too sensitive to non-linearities. Furthermore, the limits from IBS at lower energies have to be re-considered and might result in a slightly reduced number of ions per bunch. Despite of these (minor) restrictions, it looks like this option remains very interesting in terms of its physics potential.

Here again, trying to operate the LHC under these conditions implies a perfect understanding of the machine behaviour and therefore cannot be considered for the initial phase of LHC operation.

6.3 ALICE operation with protons

For the sake of completeness, a few words are in order as far as the calibration of the ALICE detector during regular proton operation is concerned. In this particular mode of operation, the luminosity in ALICE has to be reduced by at least three orders of magnitude as compared to the others experiments [7]. To this end, two measures are

presently considered: first to displace the beams in order to collide the transverse tails of the bunches and secondly to operate with a so-called "high-β" at the interaction point. It is worth recalling that in order to satisfy the constraints of regular operation (e.g. nominal luminosity and bunch spacing), the value of the β-function in ALICE cannot exceed a value around 35 m. This upper value allows therefore a luminosity reduction by a factor of 70 maximum, while the remaining reduction factor will have to be obtained from the displacement of the beams.
Actually, β values higher than 35 m (up to 200 m) could be obtained, however only at the cost of a strongly reduced number of bunches in the machine, requiring a dedicated mode of operation, very different from the official pre-requisite to be transparent to the nominal operation of the machine.

7 Summary

The aim of this report is to present a complete review of the programme for the LHC with ions. In a first step, the modifications of some basic boundary conditions such as the cross-sections for nuclear effects, the possibility of more than one experiment operating and the introduction of a new limitation (quench limit) have been presented. It is shown that these modifications will have serious implications on the future performance of the machine, in particular for the nominal ion programme related to Pb-Pb collisions. For the latter, the combination of the new parameters will result in a significant decrease of the performance in terms of integrated luminosity. As a consequence, the introduction of a dedicated mode of operation where the luminosity could be kept constant during a non-negligible part of the fill (β-squeeze during physics) might prove to be an essential ingredient for the operation with Pb ions, and the practical implementation of such a scheme definitively deserves attention.
A logical extension to the nominal ion programme (referred to as Phase II) is then presented. It consists mainly in a new list of potential candidates for collisions with lighter ions. As far as this category is concerned, it is shown that the main limitations originate either from the source or from IBS considerations. The corresponding ultimate initial performance for some of these candidates are extremely challenging (very high initial luminosities), however, the related luminosity half-lives remain significantly lower than what had been anticipated in 1995.
The final part of the report deals with a possible "upgrade programme" where hybrid collisions are discussed. It is shown that p-A collisions are not expected to present any major difficulties and that, provided the source could allow for a rapid change between the production of protons and deuterons, d-A collisions should also be possible. However, for the time being, collisions between two different type of ions (A-B collisions) are excluded from the programme. Finally, some non-standard operation scenarios like the possibility of squeezing the β-function during physics or colliding the beams at intermediate energies have also been included. The reason for a discussion of these particular schemes in the frame of the upgrade programme is motivated by the fact that such schemes represent real challenges in terms of machine operation and can therefore only be contemplated once the machine behaviour is perfectly understood and controlled.

8 Ackowledgements

I would like to thank P. Lefèvre for emphasising the need for an updated review of the LHC ion programme. Special thanks are due to D. Möhl for many useful discussions and for his careful checks of the compatibility between the numbers presented in this report and the possibilities of both the source and the injectors chain. Thanks also to B. Jeanneret and S. Klein (Berkeley) for identifying and evaluating the implications of the quench limit for the LHC performance and to P. Grafström and K. Hencken (Uni Basel) for their contributions to the correct evaluation of the updated cross-sections for nuclear effects.

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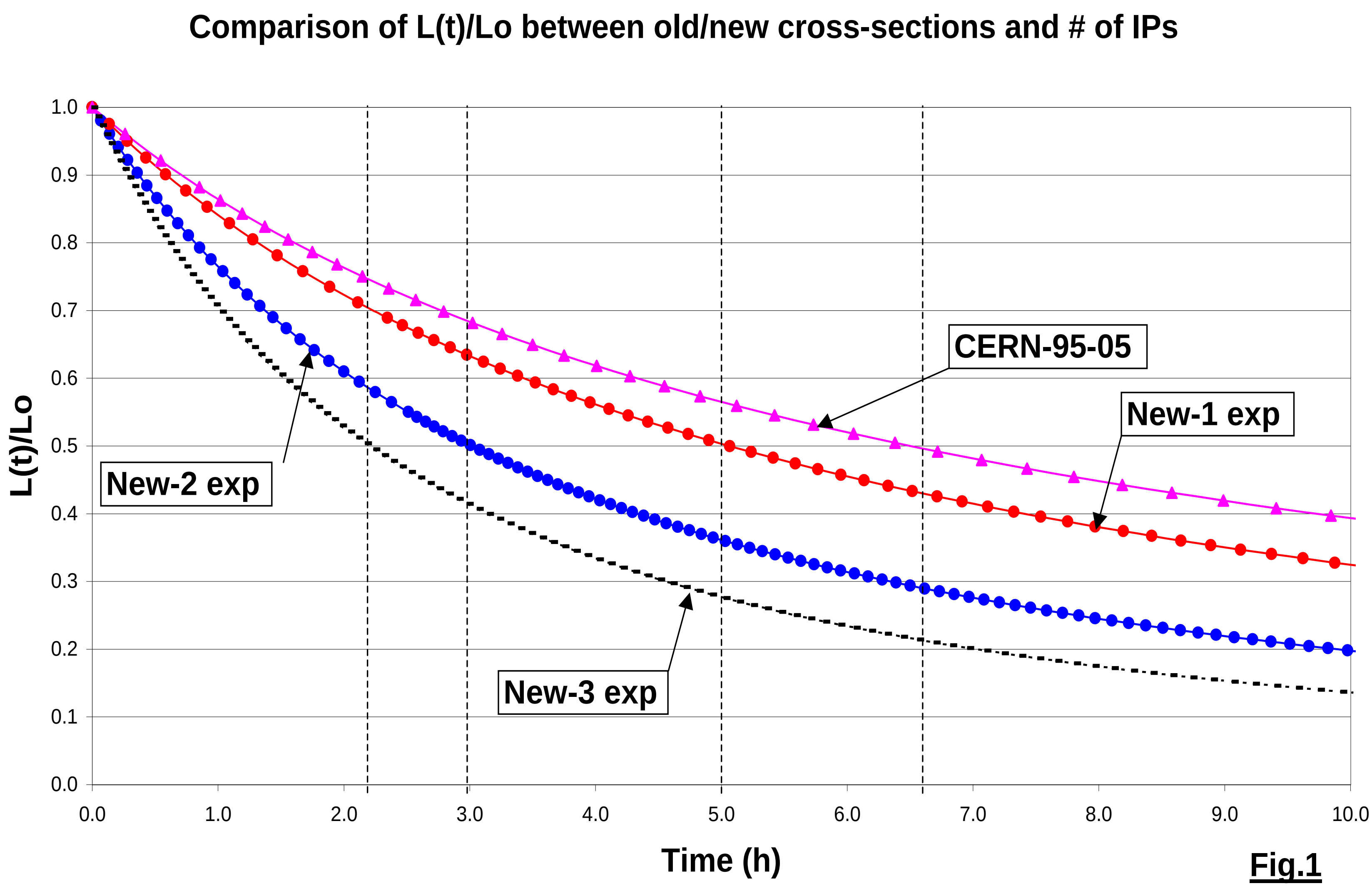

Figure 1: Cumulative effects of both the new cross-sections for nuclear effects and several experiments operating.

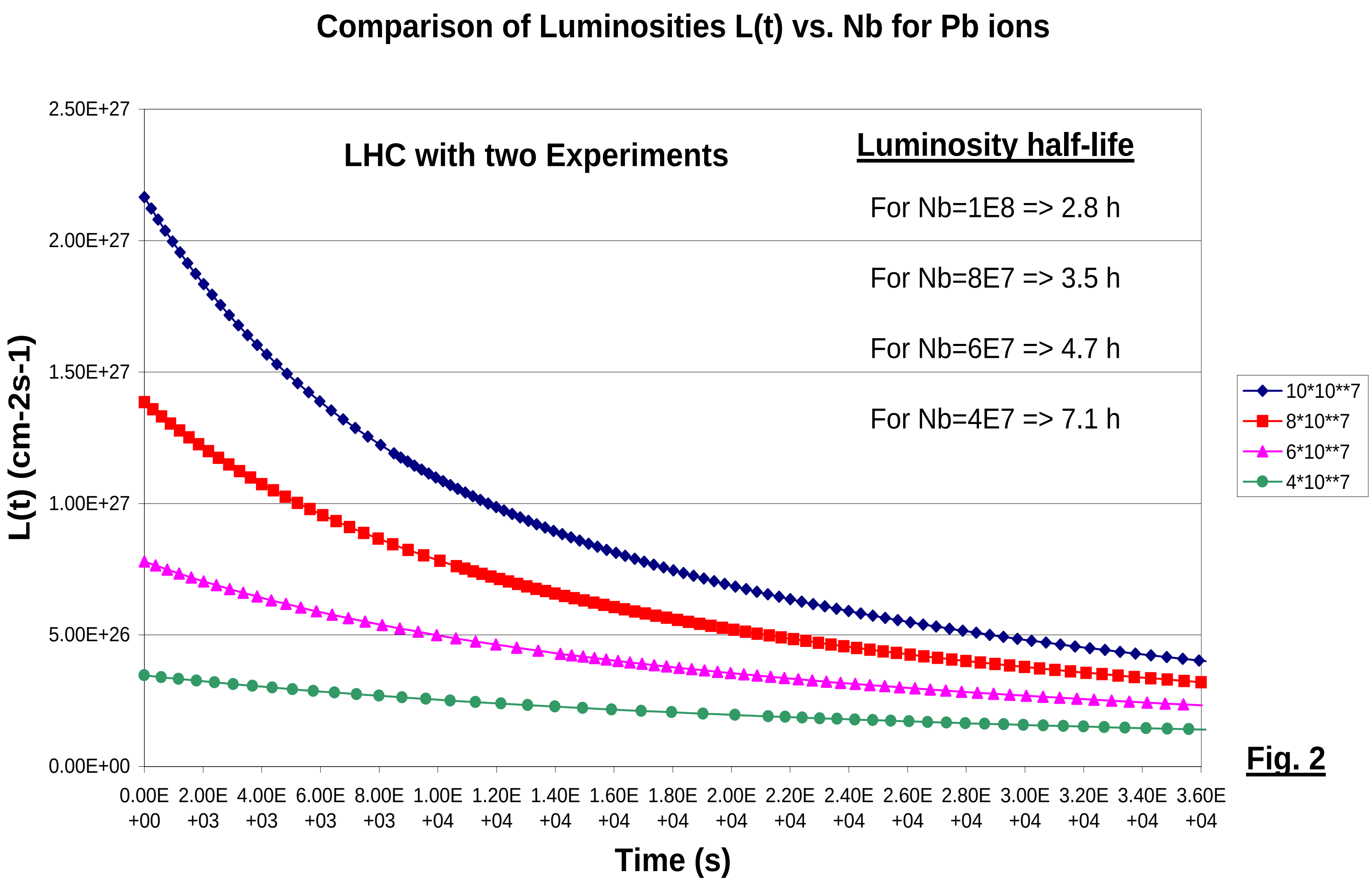

Fig. 2

Figure 2: Luminosities and luminosity half-lives for different initial bunch intensities. LHC with Pb ions and two experiments.

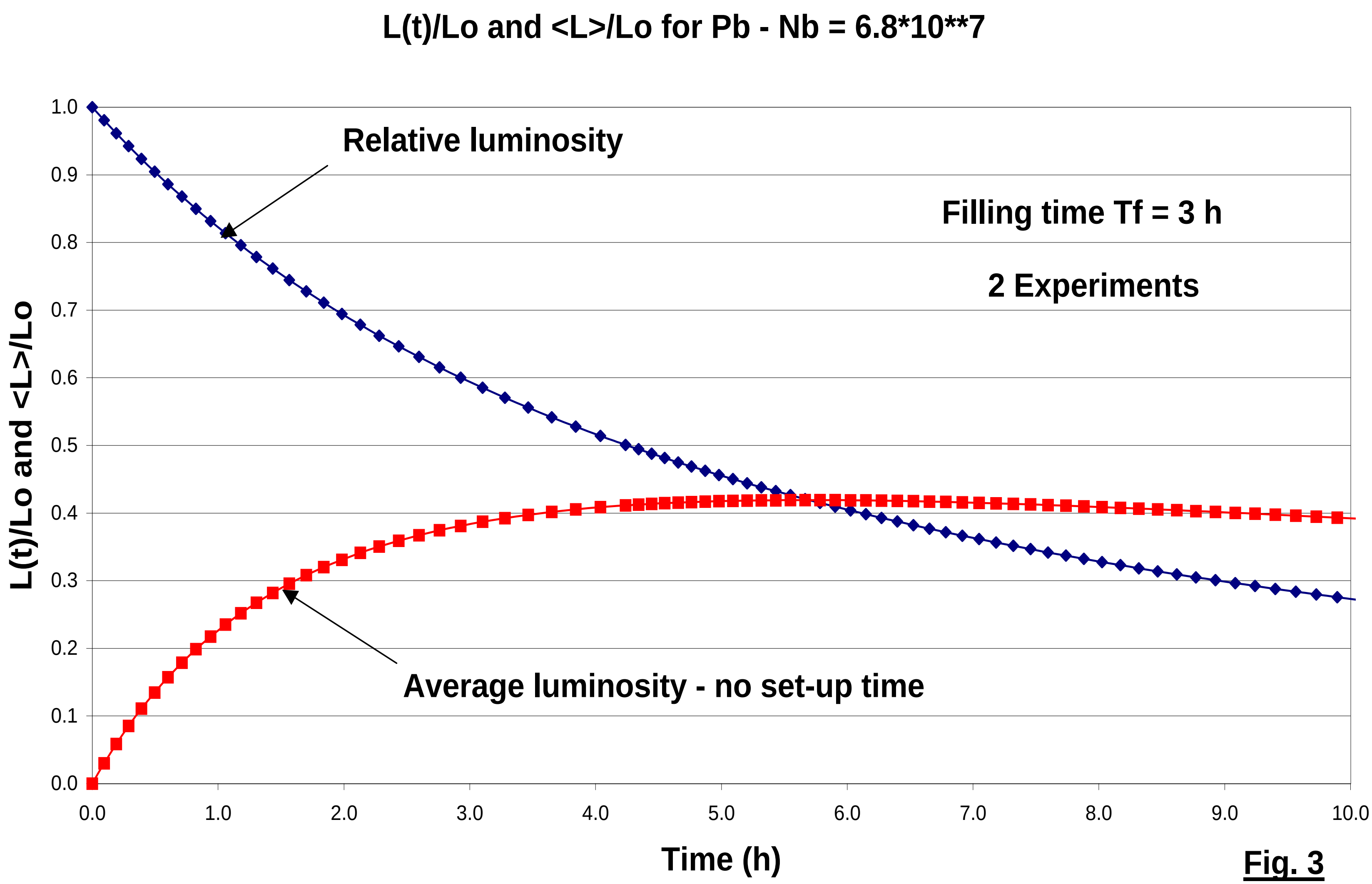

Figure 3: Relative luminosity and average luminosity for nominal operation with Pb ions and two experiments.

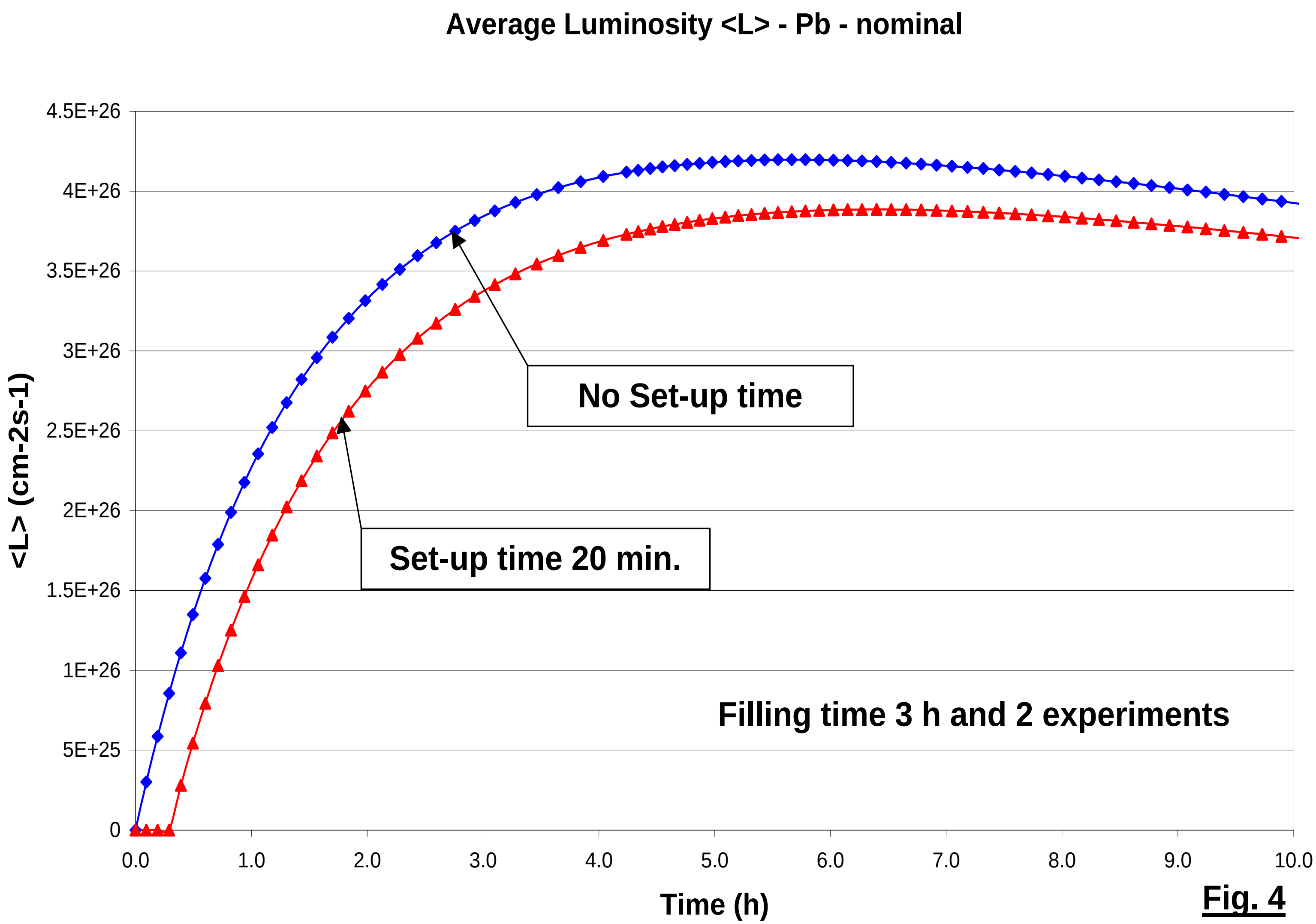

Figure 4: Effect of the set-up time on the average luminosity. Nominal conditions for Pb ions, with two experiments.

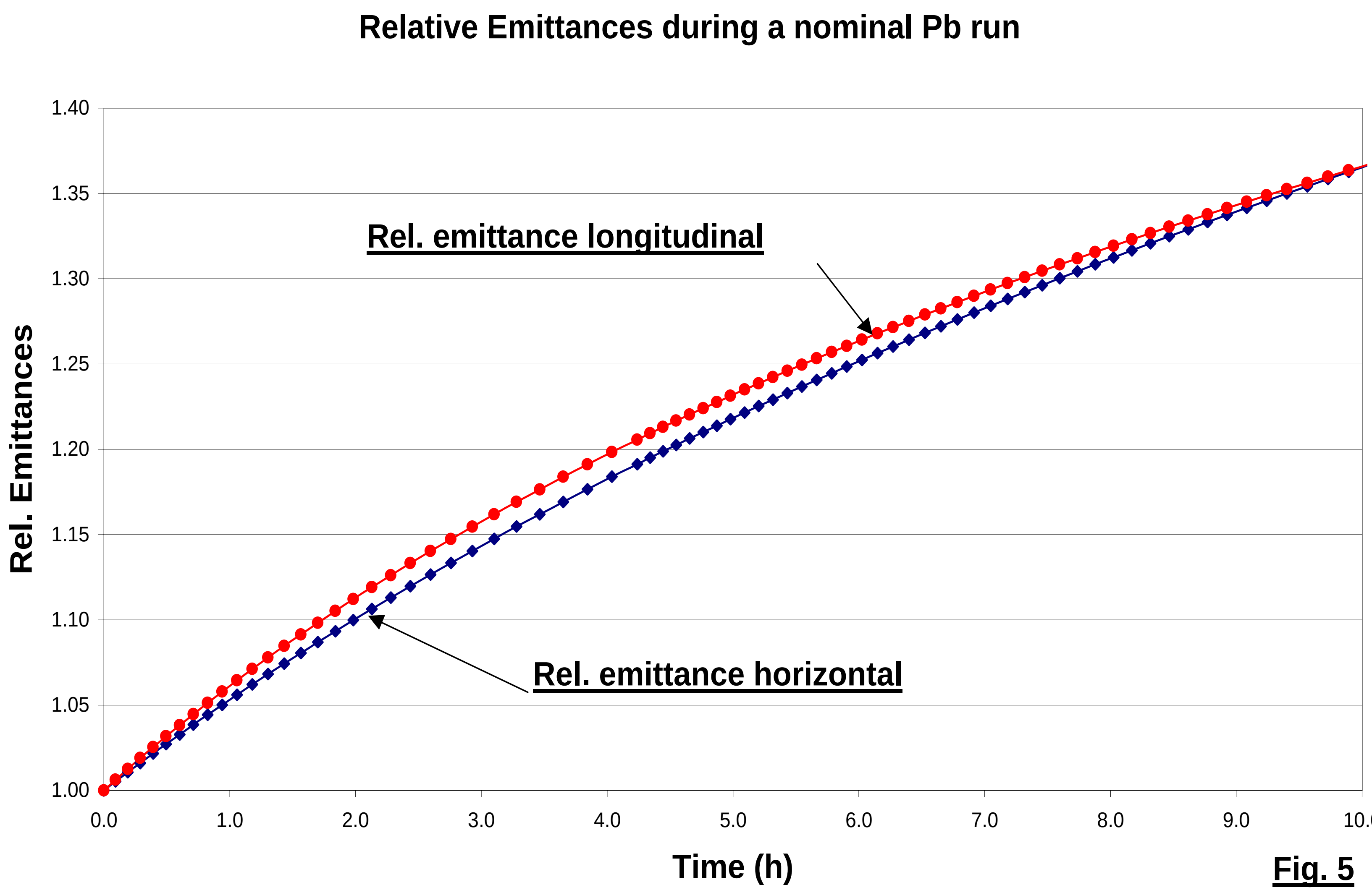

Fig. 5

Figure 5: Relative blow-up of the emittances due to IBS for a nominal operation with Pb ions and two experiments.